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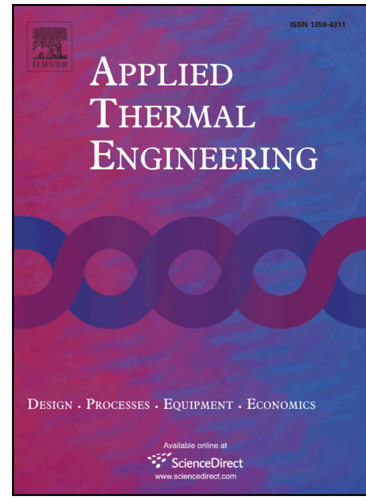

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Thermal performance of a room with a double glazing window using glazing available in Mexican market

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Abstract

A thermal thermal evaluation of a four configurations of double glass window (DGW) coupling to a room is presented. The DGW consists of two vertical semitransparent walls separated by a 12 mm air gap. The effect of varying the ambient temperature and the incident solar radiation in the warm climate conditions in México is analyzed. Numerical simulations were conducted for four configurations; *Case 1*: clear glass + air gap + clear glass (Reference); *Case 2*: clear glass + air gap + absorbent glass; *Case 3*: clear glass + air gap + Low-e glass; and *Case 4*: clear glass + air gap + reflective glass. Optical transmittance and specular reflectance were measured individually and in one sample piece for each case. The results showed that *Case 4* reduces the heat flux to the indoors by up to 73%, with respect to *Case 1*. Moreover, *Cases* 2 and 3 had a similar behavior, obtaining a reduction of indoor heat flow close to 33.5% with respect to *Case 1*. *Case 4* is the best option for energy savings in a warm climate, where it is possible to save up to $20.29 USD per kWh per year, in comparison

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to *Case 1*. In addition, the payback period for *Case 4* is 3.7 years. Therefore, the use of reflective double pane window is highly recommended in Mexican warm climates.

Keywords: Double pane window, Reversible window, Solar control, Transient analisys

1. Introduction

Human beings spends most of their lives inside of houses and buildings, performing their daily activities, such as work and recreation. These buildings use openings (enveloping windows) that allows visual contact with the environment, which has a beneficial effect on the mood of the occupants. A study conducted by Kuller and Lindsten [1] showed that the absence of natural light (in building without windows and with artificial ligthing) in a group of children caused alterations in basic hormonal patterns, and this in turn affected the ability of these children to concentrate and cooperate. For this reason, the construction of buildings with large window areas has increased over the last several decades. However, such buildings consume a large amount of energy (due to solar heat gain through windows) to maintain comfortable conditions if suitable windows designs are not used. To overcome this problem, building designers have employed different window configurations that use a wide variety of glass types (monolithic, tempered and laminated) with absorbent, reflective, and low emissivity among the most widely used.

In the last decade, research related to different configurations of double-pane windows has been developed, for example, DGW with air enclosed [2–4] or with some inert gas [5–8] with dynamic water as the thermal fluid [9, 10], with natural convection [11–14], with enclosed slats or blinds [15, 16], those that use phase change material [17–19], transparent solar cells [20, 21] and aerogel [22, 23]. Among the existing high-performance windows, double- and triple-glazed multilayer windows are the most commonly used because of their low cost with respect to other DGW configurations, although vacuum glazing and aerogel are expected to dominate the market in the near future, according to a recent study presented by [24].

Double-glazed windows have proven to be the best option for saving energy in buildings, in most climates, due to the air or gas space between the panes that serves as an excellent thermal barrier, compared to monolithic energy flux through older buildings. Many studies related to DGW with air enclosed have been conducted over the years. Among the first works reporting on the thermal performance of double glazing were those made by Eckert and Carlson [25] and Christensen et al. [26], who conducted theoretical and experimental studies, respectively, to examine the details of heat transfer through the air space in double-glazed, unvented windows. Data obtained by Christensen agreed reasonably well with the interferometric data obtained by Eckert and Carlson. Some years later, Selkowitz [27] presented a study of the thermal performance of window insulation systems. His main findings were that despite double glazing cutting heat losses from single glazing by approximately 50%, there are better options that could reduce heat losses up to 90%, such as double glazing with heat mirrors.

Similar results were obtained by [2] and [28] in which the optimal gap width was found to be near 20 mm for different locations. Additionally, in several works, such as Ismail [11], it was found that the air gap width in double pane window has no significant impact on the mean coefficient of the solar heat gain (SHGC) and the mean shading coefficient (SC); Ismail et al. [18] conducted an analysis to compare thermal efficiency for two types of double pane window -one filled with an absorbing gas and the other filled with a phase change material (PCM) and exposed to solar radiation in a hot climate; they found that double-pane window filled with an absorbing gas mixture and using reflective glass is more efficient ($\simeq 10\%$) than those using PCM. Finally, they found that DGW with absorbing gas filled is more effective than a natural ventilated double glass window or simple glass window [29]. Meanwhile, Chow and collaborators proposed the concept of a water-flow window and discusses its potential applications [30]. They used 36 types of glass, -single and different types of DGW with and without solar control film. The thermal evaluation was conducted with commercial software window 5.2.17 and Optics 5.1. The results obtained show a reduction of up to 91% with respect to incident solar radiation using a Low-e configuration & reflective configuration on clear +Air+Clear glass. The results presented a better behavior than for ventilated, airflow, and water-flow DGW, and are highly suitable for applications in warm and temperate climates.

From the literature, it can be concluded that there are plenty of studies related to the thermal performance of different types of double-pane window in steady state. However, there are scarce studies related to thermal performance in transient state of double-pane glazing [29, 31]. In addition, several of these works use correlations for convective and radiative heat transfer coefficients for convection and radiation between the glass and the fluid.

Therefore, the main goal of this paper is to evaluate the pseudo-transient thermal performance (each hour) of four types of double-pane window coupled to a room, in the warm climatic conditions of México (Ciudad Juárez, México), which are representative of almost the entire country, see Fig.1. The thermal analysis of four DGW configurations will allow knowing which case presents a better 24-hour thermal performance, to reduce the amount of energy gained towards the inside environment of the room. It is important to mention that all glazing used in this work is available on Mexican market. This numerical study does not use correlations of convective and radiative heat transfer coefficients, because they are considered, through the governing equations to model the Room-DGW.

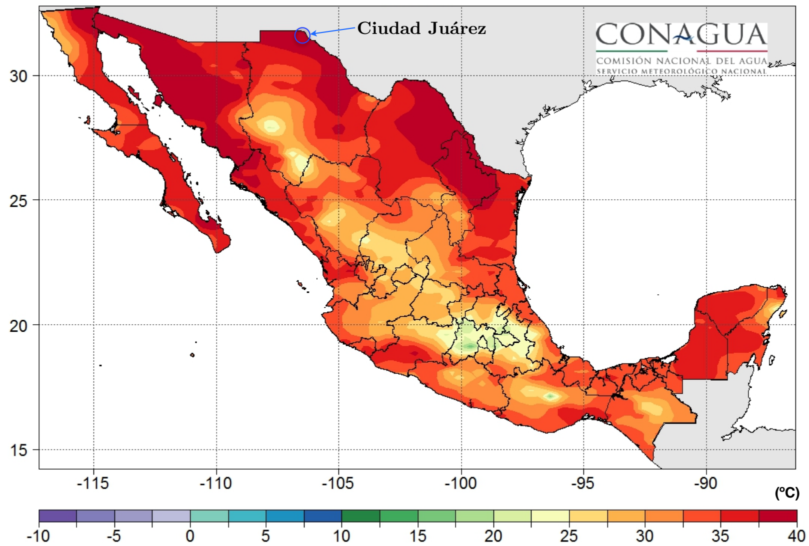

Figure 1: Monthly average maximum temperature in Ciudad Juárez (°C) [32].

2. Physical and Mathematical model

2.1. Physical model

The geometry of the Room-Double Glazing Window is representative of a room in the middle of a multistory building, (see Fig.2). The section view (A-A') from Fig.2 is shown in Fig.3. The room is modelled as square cavity in which heat conduction, turbulent natural convection, and surface thermal radiation (conjugate heat transfer) are considered. The DGWs used are shown in the inset of Fig.3 and are constructed using window glass available in Mexican market, such as absorbent, clear, low emissivity and reflective glazing. These DGWs were considered as a tall cavity and were coupled to the model of the room as boundary conditions. The double glass window coupled to the room (henceforth Room-DGW) can be assumed to be of infinite depth along the z-axis. The room has a height and a width of 3 m ($H\!=\!W$). The Room is composed of two horizontal adiabatic walls; the left vertical isothermal wall is at 24°C (T_2) and the right wall is partially adiabatic and with a DGW.

Two-dimensional flow is considered because the dimension in z direction is much longer than the other two and natural convection and surface thermal radiation inside the room is considered. The height of the window with double glass is 0.8m (H_2), and the glass thickness is 6mm each. The heigth from the floor to the base of the window, is 1.2 m (H_1).

Figure 2: Representation of the double glazing window coupled to a room in a multistory building.

The physical model representing the DGW is shown in Fig.3, which consists of two vertical semitransparent walls: glazing-1 facing indoor air at temperature (T_{int}) and glazing-2 facing outdoor air at temperature (T_{ext}) and exposed to solar radiation (G). The gap between both glazings has a length of b. The top and bottom walls are adiabatic and laminar natural convection and surface thermal radiation along the cavity walls is considered. Heat transfer through the semitransparent walls occurs by conduction. In the inset of Fig. 3 the heat transfer mechanisms in the double glass window are shown. Glass-2 is a clear, absorbent, Low-emissivity or reflective glass. Solar radiation (G) arrives to this glass, and part of this energy is reflected and absorbed by the glass and transferred towards inside to the cavity. The energy passing through Glass-2 (G_1) impacts directly on the Glass-1, and part of this energy is reflected and/or absorbed through this glass and transmitted to the inside environment. The transmitted energy arriving to the inner medium is the product of solar irradiance (G) and the transmittance of each element of the DGW. The total absorbed energy is the sum of the absorbed energy by each glass layer and due to this absorbed energy, the two glass layers have a variation of their internal energy manifested in a change of their temperature; as a consequence, both glasses exchange thermal energy by radiation and convection with their surroundings, towards the interior (q_{int}^{conv} and q_{int}^{rad}), the exterior (q_{ext}^{conv}, and q_{ext}^{rad}), and the space (q_{g1}^{conv}, q_{g1}^{rad}, q_{g2}^{conv} and q_{g2}^{rad}) between them. The fluid inside the room and the DGW was assumed to be air and their properties were assumed to be constant, with the exception of the density in the buoyancy force term in the momentum equations, according to the Boussinesq approximation. The air was considered radiatively non-participating.

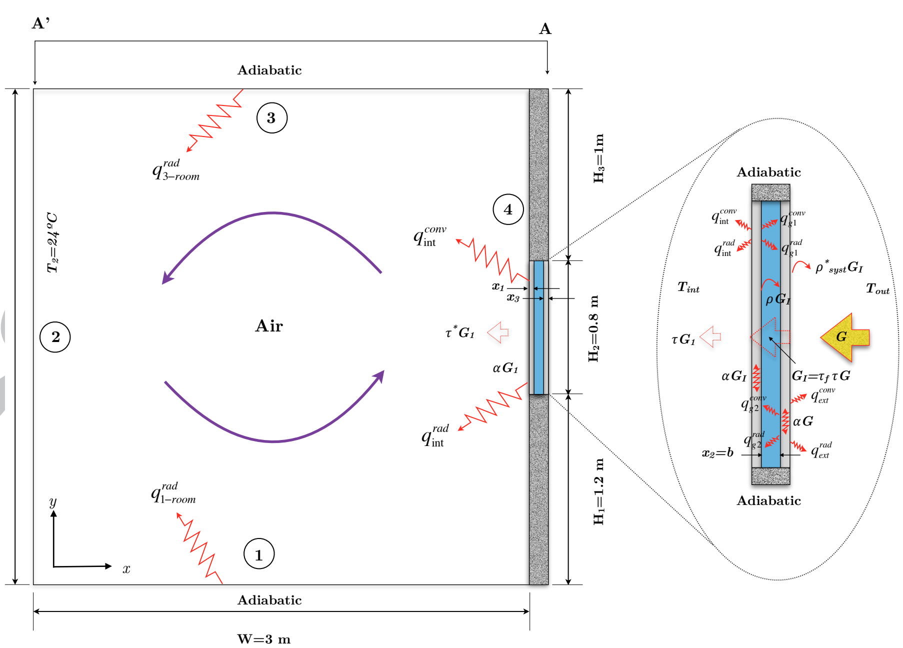

Figure 3: Physical model representing the double glazing window coupled in square cavity.

2.2. Mathematical Model for the Room

2.2.1. Turbulent Natural Convection Model for the Room

The governing equations for turbulent natural convection in the room are the average equations of mass, momentum, and energy. The equations are expressed as:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial(\rho u_j u_i)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \rho\overline{u_i' u_j'}\right] - \rho\beta(T - T_0)g^* \tag{2}$$

$$\frac{\partial(\rho u_i T)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\frac{\lambda}{C_p}\frac{\partial T}{\partial x_i} - \rho\overline{u_i' T'}\right], \tag{3}$$

where the Reynolds stress tensor and the turbulent heat vector are modeled as $-\rho\overline{u_i' u_j'} = \mu_t(\partial u_i/\partial x_j + \partial u_j/\partial x_i) - (2/3)\rho k\delta_{ij}$ and $-\rho\overline{u_i' T'} = (\mu_t/\sigma_T)\partial T/\partial x_i$, respectively. The turbulent viscosity can be obtained as $\mu_t = C_\mu \rho k^2/\varepsilon$. The turbulent kinetic energy (k) and the turbulent dissipation of kinetic energy (ε) can be obtained using the corresponding transport equation [33]. Velocity boundary conditions on the walls are zero and the temperature boundary conditions are set as the adiabatic horizontal walls (up and bottom), the left vertical wall is isotherm, and heat transfer by conduction is considered at glass-1 (partial right wall), that is:

$$\text{Glass-1 (partial wall 4,}\;\; H_1 \leq y \leq H_2) : q_{g1}^{cond} = q_{int}^{conv} + q_{int}^{rad} \tag{4}$$

$$\text{Right adiabatic wall (wall 4, } 0 \leq y < H_1 \text{ and } H_2 < y \leq H_3) : 0 = q_{4-Room}^{cond} + q_{4-Room}^{rad}, \quad (5)$$

where q_{int}^{conv} (q_{4-Room}^{cond}) is the conduction heat flux from the inner surface to the adjacent fluid on wall 4. The term q_{int}^{rad} (q_{4-Room}^{rad}) is the net radiative heat flux over wall 4. Finally, q_{g1}^{cond} is the heat flux by heat conduction through glass-1. The net radiative method was used to calculate the resulting heat fluxes from the radiation exchange in the walls of the room [34]. The two horizontal surfaces and the left vertical wall of the room are assumed to be opaque and diffuse, whereas the partial right wall is semitransparent. The surface thermal radiation model was presented by Xamán et al. [4, 35].

2.3. Mathematical Model for the DGW

2.3.1. Laminar Natural Convection Model for the DGW

The mathematical model for the double glazing window has been presented in different articles by the authors [36, 37]. Therefore, the corresponding mathematical model will be described only briefly. The mathematical models for laminar natural convection inside the double glazing are the conservative equations of mass, momentum, and energy. The boundary conditions in the solid walls for the fluid are assumed to be zero velocity. Adiabatic conditions are given at the top and the bottom of the walls and an energy balance between the corresponding glass on the vertical boundaries and the air is carried out. That is:

$$-\lambda_g \frac{\partial T_{g1}}{\partial x} = q_{g1}^{conv} + q_{g1}^{rad} \qquad \text{for} \qquad x = W + x_1, \qquad H_1 \leq y \leq H_2, \qquad (6)$$

$$-\lambda_g \frac{\partial T_{g2}}{\partial x} = q_{g2}^{conv} + q_{g2}^{rad} \qquad \text{for} \qquad x = W + x_1 + x_2, \qquad H_1 \leq y \leq H_2, \tag{7}$$

where q_{g1}^{conv} and q_{g2}^{conv} are the convection heat transfer fluxes from the inside surface to the adjacent fluid on glass-1 and glass-2, respectively. The terms q_{g1}^{rad} and q_{g2}^{rad} are the net radiative heat transfer flux at glass-1 and glass-2. Finally, $\lambda_g \partial T_g/\partial x$ is the heat flux by heat conduction through the corresponding semitransparent wall. The net radiative method was used to calculate the resulting heat fluxes from the radiation exchange inside DGW. The differential equation to obtain the temperature distribution for Glass-1 and Glass-2 is:

$$\frac{\partial}{\partial x}\left(\frac{\lambda_g}{C_{pg}}\frac{\partial T_g}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\lambda_g}{C_{pg}}\frac{\partial T_g}{\partial y}\right) + \frac{1}{C_{pg}}\frac{d\Theta(x)}{dx} = 0 \tag{8}$$

where $\Theta(x) = G\exp\left[-s_g(w-x)\right]$ is function of the glass extinction coefficient s_g [34], and $w(x_1$ or $x_3)$ is the glass thickness.

The vertical boundary conditions on Glass-2 are

$$-\lambda_g \frac{\partial T_{g2}}{\partial x} = h_{\text{ext}}\left(T_{\text{g2}} - T_{\text{ext}}\right) \quad +\sigma\varepsilon_{\text{g}}^{*}\left(T_{\text{g2}}^{4} - T_{\text{ext}}^{4}\right) \quad \text{for} \quad x = W + x_1 + x_2 + x_3, \quad H_1 \leq y \leq (H_1 + H_2), \tag{9}$$

$$-\lambda_g \frac{\partial T_{g2}}{\partial x} = q_{g2}^{conv} + q_{g2}^{rad} \quad \text{for} \quad x = W + x_1 + x_2, \quad H_1 \leq y \leq (H_1 + H_2), \tag{10}$$

and the vertical boundary conditions on Glass-1 are

$$-\lambda_g \frac{\partial T_{g1}}{\partial x} = q_{int}^{conv} + q_{int}^{rad} \quad \text{for} \quad x = W, \quad H_1 \leq y \leq (H_1 + H_2), \tag{11}$$

$$-\lambda_g \frac{\partial T_{g1}}{\partial x} = q_{g1}^{conv} + q_{g1}^{rad} \quad \text{for} \quad x = W + x_1, \quad H_1 \leq y \leq (H_1 + H_2), \tag{12}$$

Equations 6 to 12 are applied in all configurations analyzed (see Fig.4).

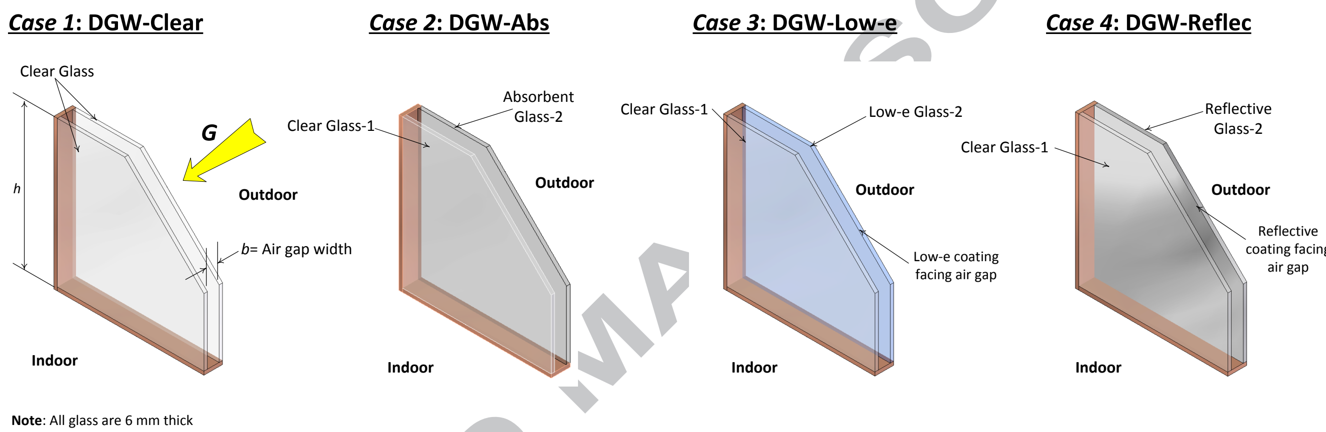

Figure 4: Configurations of DWG used in thermal analysis.

3. Optical properties of DGW

As noted above, the DGW consists of two glass panes separated by air or another gas filled space to reduce heat transfer across a part of the building envelope. Because the optical properties of the whole assembly are required for the model, the optical properties of the four cases were measured on a Shimadzu Spectrophotometer 3100 PC. In reference [38], a detailed explanation of optical characterization was made by the authors. Table 1 shows the optical properties of the DGW used in this work. The optical properties of the single glass used to construct the DGW are presented in Table 2. The specular reflectance of the reflective and Low-e glass was measured on both sides (film side and glass side). In the third column of

Table 2 both values for glass reflectance are shown. According to the Kirchhoff's relationship, within any specified waveband of the electromagnetic spectrum, the sum of the absorptance (α^*), transmittance (τ^*), and reflectance (ρ^*) of a material will equal one. Therefore, the fourth column also has two values.

Table 1: Physical properties of four types of double glass.

Glass Type	τ^*_{Sol} [%]	ρ^*_{Sol} [%]	α^*_{Sol} [%]	ε^*_g [adim]
Double Clear Glass, 24 mm thick	0.62	0.12	0.26	0.850
Double Absorbente, Glass 24 mm thick	0.37	0.11	0.52	0.840
Double Low-E Glass, 24 mm thick	0.37	0.05	0.58	0.837
Double Reflective, Glass 24 mm thick	0.07	0.29	0.64	0.840

Table 2: Pysical properties of single glass used to construct DGW.

Glass Type	τ^*_{Sol} [%]	ρ^*_{Sol} [%]	α^*_{Sol} [%]	ε^*_g [adim]
Clear Glass, 6 mm thick	0.84	0.09	0.07	0.850
Absorbente, Glass 6 mm thick	0.47	0.07	0.46	0.840
Low-E Glass, 6 mm thick	0.44	0.2/0.39[a]	0.36/0.17	0.837
Reflective Glass, 6 mm thick	0.08	0.30/0.51	0.62/0.41	0.840

[a] The first value corresponds to the film side, the second glass side

The solar control parameters, such as total solar transmittance (τ^*_{Sol}) and total solar reflectance (ρ^*_{Sol}) were evaluated for D65 spectrum according to the procedure described in the ISO 9050 standard [39].

4. Methodology for the Numerical Solution

4.1. Numerical Method

The numerical solution methodology, mainly used to solve the problem of conjugate heat transfer in the room, is based on the finite volume method, which it was implemented by the authors over a decade ago. Therefore, the numerical code used in this work to model the Room-DPW is based on the computational platform developed by the authors, who have presented verifications and validations for different CFD problems in several publications, which can be found in [40–44]. It was decided not to include validations and verifications previously mentioned in other publications, and so these were not reported again here. A brief introduction to numerical methodology used is presented below. The equations for the convective (turbulent and laminar) and conductive models are integrated over the element control volume located around each node of one numerical mesh. The convective terms are discretized by applying the hybrid scheme and the diffusive terms with the central scheme. Coupling between momentum and continuity equations was carried out through the SIMPLEC algorithm [45]. The resulting algebraic equations system was solved by applying the LBL-ADI method. A radiative balance over the walls was solved using an iterative approach in order to couple conjugate heat transfer to surface thermal radiation effect at the boundaries.

The general procedure for the Room-DGW can be summarized in the following steps [46]:

- View factors (room and DGW) were computed.
- Initial guess values of all variables ($u, v, P, T, T_g, ...\varepsilon$) in the room and the double glazing window were given.
- Radiative balance over the walls was computed in the room in order to obtain the local radiative heat flux on the walls.
- The net radiative method was used to calculate the resulting heat fluxes from the radiation exchange in the walls of the DGW.
- The conductive model was solved for Glass-1 and Glass-2.

- The pressure and velocity components in the DGW were calculated by the SIMPLEC algorithm and the temperatures inside the DGW were obtained.

- The pressure-velocity (u, v, P) was calculated by the SIMPLEC algorithm for the room.

- With the new calculated values of local radiative heat flux and velocity, the temperature, the turbulent kinetic energy, and the turbulent dissipation of kinetic energy field in the room were obtained.

- A convergence criterion was applied as 10^{-10} for each equation, and the process was repeated iteratively until the convergence criterion was achieved.

The accuracy of the numerical results was verified through numerous tests based on the grid size effect. The grids considered were from 61x61 to 111x111 and the 71x51 to 111x91 for the room and the DGW, respectively. Based on numerical calculations, the computational grid that gives grid independent solutions was 182x162 with nonsignificant differences (1.0 %) for the components of velocity and for the temperature profile at the center of room and the double glass window.

5. Results and Discussion

To model the thermal performance and the thermal evaluation of the Room-DGW over 24 hours (one day), the meteorological conditions for the warmest day (July 21st, 2015) in Ciudad Juárez, Chihuahua were used as input data. A metorological database was obtained via Meteonorm commercial software [47]. The parameters used in Room-DGW were the following: *i*) square room of $H=$ 3 m in size; *ii*) a window height of H_2=0.8 m; *iii*) a gap width of b=12 mm (x_2 in equations 7, 8 and 9) for DGW (distance between the glass layers); *iv*) opaque wall emissivity equal to ε^*=0.85, and *v*) outdoor convective heat transfer coefficient equal to h_{ext} =6.8 W/m^{2}K. Each DGW was constructed using four different types of glass on the outer side: clear, absorbent, low emissivity, and reflective glass, all 6 mm thick. In all cases, the internal glass used was clear 6 mm glass. In Fig.4 the DGW configuration used can be observed. Another parameter used in the model was solar radiation (G) incident on the exterior glass wall and the outdoor temperature (T_{ext}) (see Table 3). In the analysis of Room-DGW, four configurations were used: *Case 1*: Double Clear Glass; *Case 2*: Double Absorbent Glass; *Case 3*: Double Low-E Glass; and *Case 4*: Double Reflective Glass.

Table 3: Climatic conditions in Ciudad Juárez, Chihuahua for 2015.

Time(h)	**Warmest day** (July 21st)	
	T_{ext}[°C]	G[W/m^2]
1:00	29.1	0
2:00	29.3	0
3:00	29.5	0
4:00	29.6	0
5:00	29.7	0
6:00	30.0	6
7:00	31.7	61
8:00	33.6	81
9:00	35.5	115
10:00	37.2	147
11:00	38.8	167
12:00	40.1	170
13:00	41.2	231
14:00	42.0	441
15:00	41.2	612
16:00	41.2	738
17:00	41.2	767
18:00	41.4	708
19:00	40.3	417
20:00	39.2	0
21:00	38.4	0
22:00	37.5	0
23:00	36.6	0
24:00	29.0	0

5.1. Flow pattern inside the Room (Thermal performance)

When solar radiation affects the DWG, it absorbs a part of that energy, depending on the optical properties of the glass used in its construction. The temperature reached by the internal glass of the DWG (glass in contact with the room) has a direct influence on the temperature and on the air movement inside the room. This is because the left wall of the room is isothermal, $T_2 = 24°$C, and the remaining of the walls have a non-uniform temperature distribution, which causes air movement (natural convection) that can be upward or downward.

Fig.5 shows a comparison of the temperature of the glass in contact with the room ($T_{glass-1}^{average}$) with respect to the isothermal wall and the temperature outside the room, for the four cases analyzed.

It can be seen that the clear DGW has a maximum temperature of 33°C, while the reflective DGW has a temperature approaching 29°C. This is due to the optical transmittance of the glass in contact with the exterior of a Reflective-DGW being $\simeq$ 7%, and its reflectance $\simeq$ 30%, additionally, the 12 mm air space between glasses, incites the energy that impinges on the glass in contact with the room to be reduced considerably.

An analogous behavior is for the absorbent DGW (τ_{Sol}^{*}=0.37) and the low emissivity (τ_{Sol}^{*}=0.37), because of its similarity in optical transmittance. The average temperature in the glass in contact with the room causes movements in the interior air of the room.

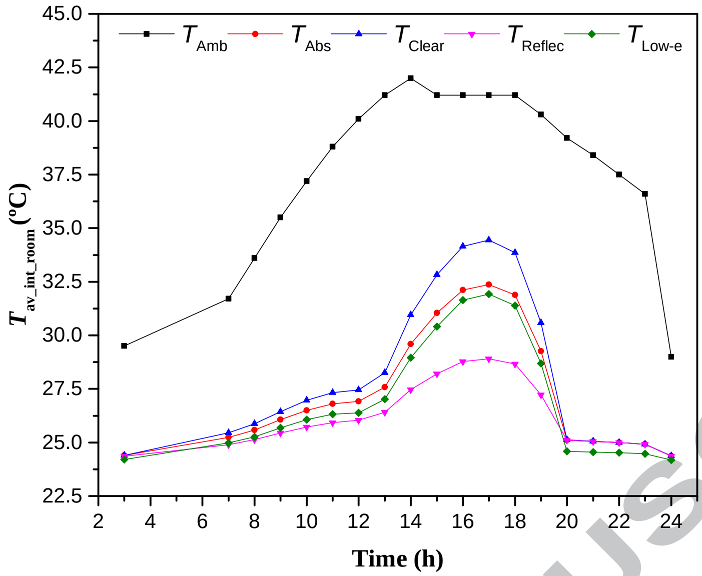

Figure 5: Average temperature of glass-1 for cases 1 to 4.

The right wall of the Room-DGW has three sections; the upper and lower sections are adiabatic and the central, which corresponds to the DGW, can have an average temperature ($T^{average}_{glass-1}$) higher or lower than that of the isothermal wall, T_2 = 24°C, depending on the ambient temperature and the incident solar radiation. Therefore, if ($T^{average}_{glass-1}$ >24°C), then the air movement is upward and if ($T^{average}_{glass-1}$ <24°C), then the movement is downward. This behavior can be seen in Fig. 6, where the current reference lines for *Case 1* and *Case 4* (Reflective DGW) are observed.

Due to the temperatures reached by the clear glass, recirculation occurs in the upper right corner, which is not observed in the absorbent glass, as it is maintained at a lower temperature and without visible changes in the circulation of the internal air. On the other hand, heat transfer through the DGW, due to the radiant solar energy it absorbs, increases the internal energy of the glass and in turn increases the temperature inside the room, causing a heat flow towards the exterior and interior of the room.

Fig.7 illustrates the temperature distribution inside the room. It can be seen that when there is no incident solar radiation in the reference window, the interior temperature remains very close to the temperature of the isothermal wall, that is, near 24°C. Startig at 7 h, the temperature rises, reaching the maximum temperature (33.8°C) at 17 h. Otherwise, the double-glazed room with reflective glass is maintained at a lower temperature (29.2°C), and close to 24°C when there is no solar radiation incident on the window.

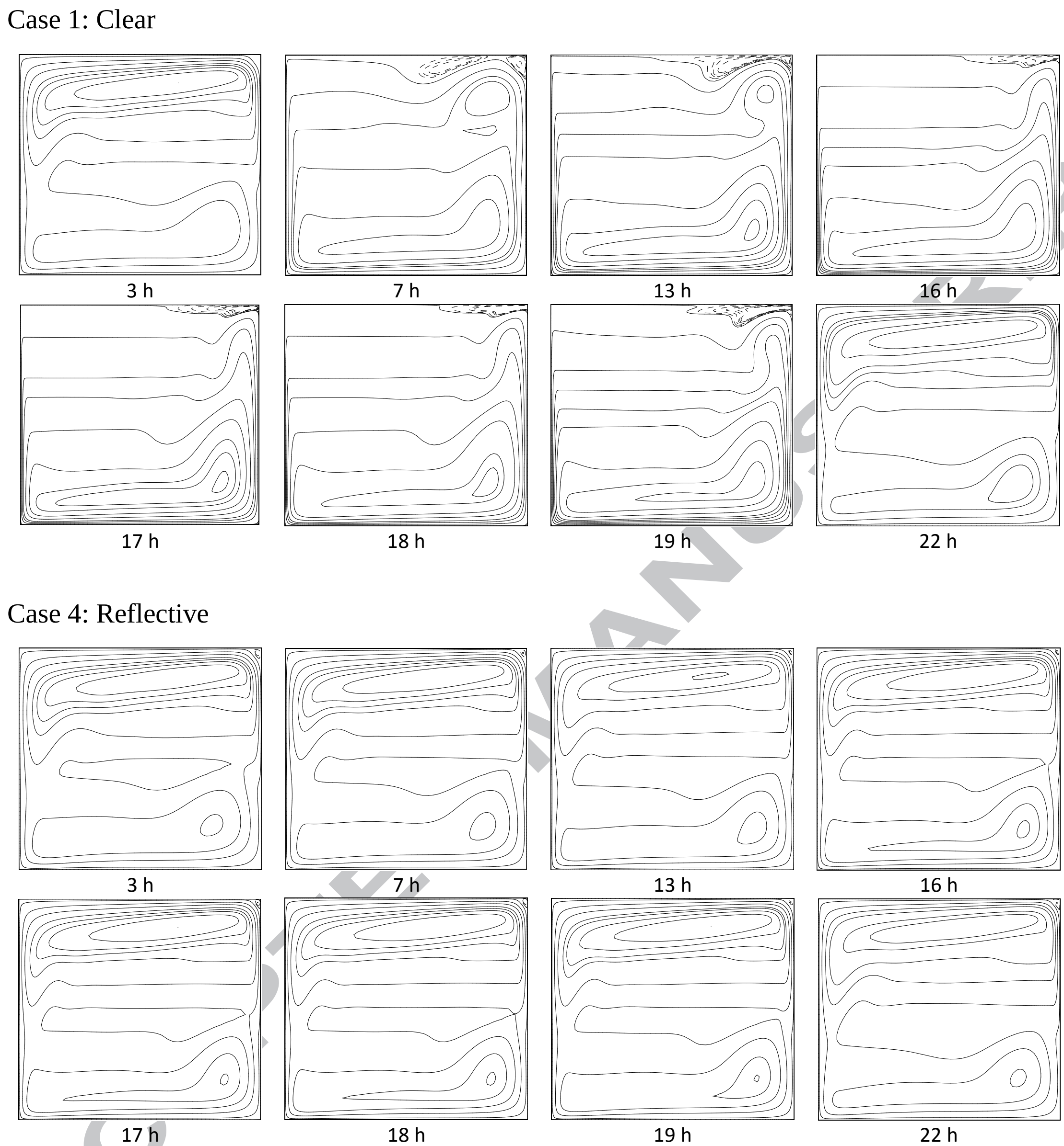

Figure 6: Streamlines for the air inside the room for cases 1 (top) and 4 (bottom).

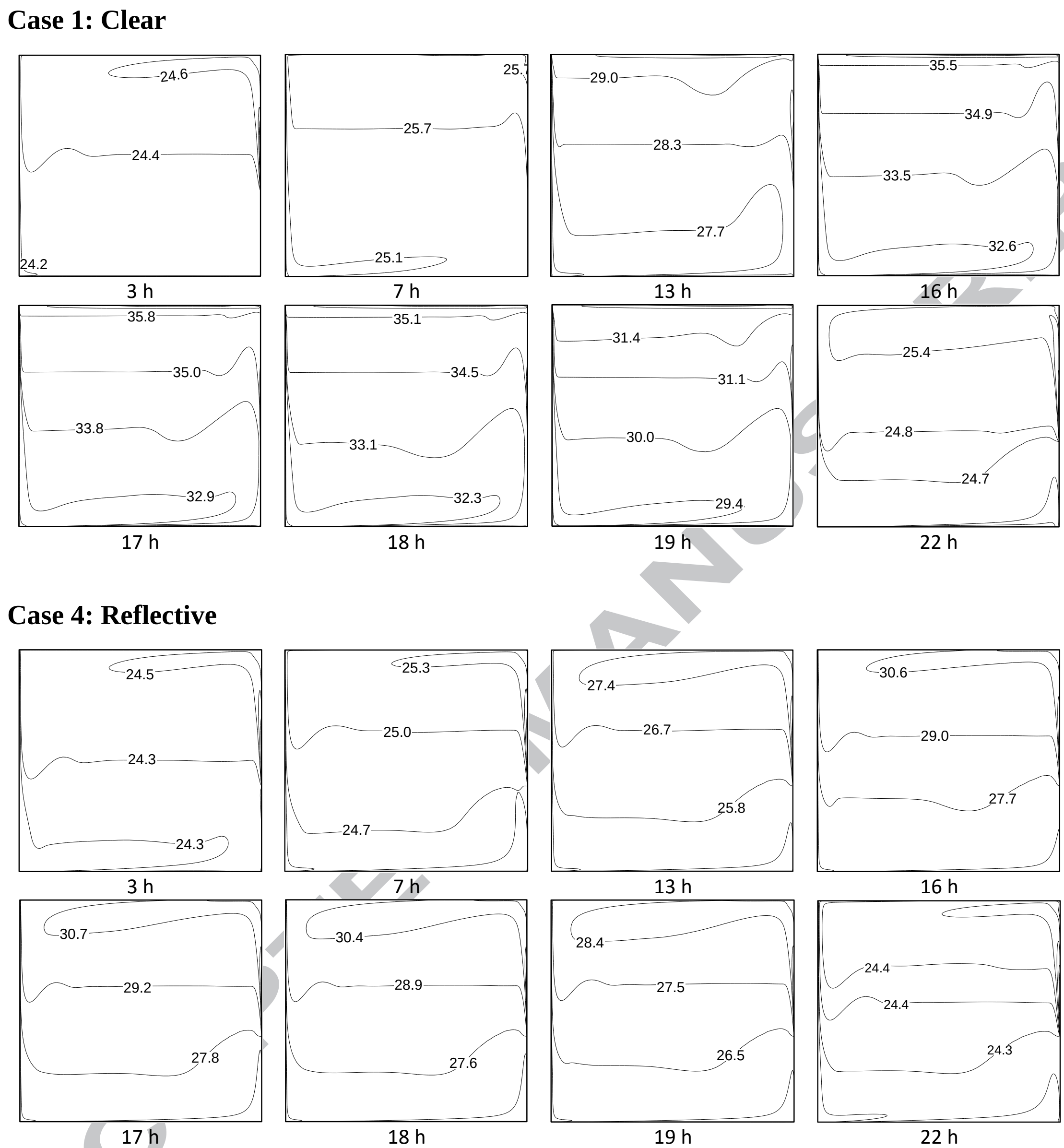

Figure 7: Isotherms for the air inside the room for cases 1 (top) and 4 (bottom).

5.2. Thermal Evaluation for the Room-DGW System

5.2.1. Thermal evaluation for warm climate condition

The parameter that allows thermally evaluating the room is the total heat flow (q_{int}^{total}), which passes through the double glazing and reaches the interior of the room. The components of the total heat flux are: convective flow (q_{int}^{conv}), radiative flux (q_{int}^{rad}), and the energy transmitted directly (q_{int}^{trans}=$\tau_g^* G$). The results of the total heat flow (q_{tot}) obtained by the room for each double glass analyzed are shown in Fig. 8. For comparative purposes, the behavior of the solar radiation with negative values is added for a better reference of the heat gain through each double glass. It is important to mention that the negative signs indicate that the heat flow is towards the interior of the room.

Fig. 8 shows maximum peaks of (q_{tot}) from -618.26 W/m^2 to DGW-Clear up to -146.85 W/m^2 for DGW-Reflective. Due to its similar absorption values, DGW-Absorbent and Low-e have similar value of $\simeq$-415 W/m^2. It can be observed that DGW-Reflective reduces the heat gain to the interior of the room to a greater extent than the others. Table 4 presents the hourly values of the heat flow inside for each DGW and the difference between the DWG with the lowest gain (*Case 4*) with respect to the reference (*Case 1*).

Although from 20 h to 6 h there is no solar radiation, the temperature difference between the outside environment and the interior of the room means that there is energy gain in the room.

In order to quantify the energy savings with the DGW analyzed, a numerical integration ($\int_{01}^{24} q(t)\, dt$) was made by the trapezoid method to obtain energy consumption per day and unit area. It is important to note that Case 4 (DGW-Reflective) it reduced to a value of 27% of the energy flow gained, with respect to Case 1 (DGW-Clear), that is, it has a savings of 73% with respect to the reference value.

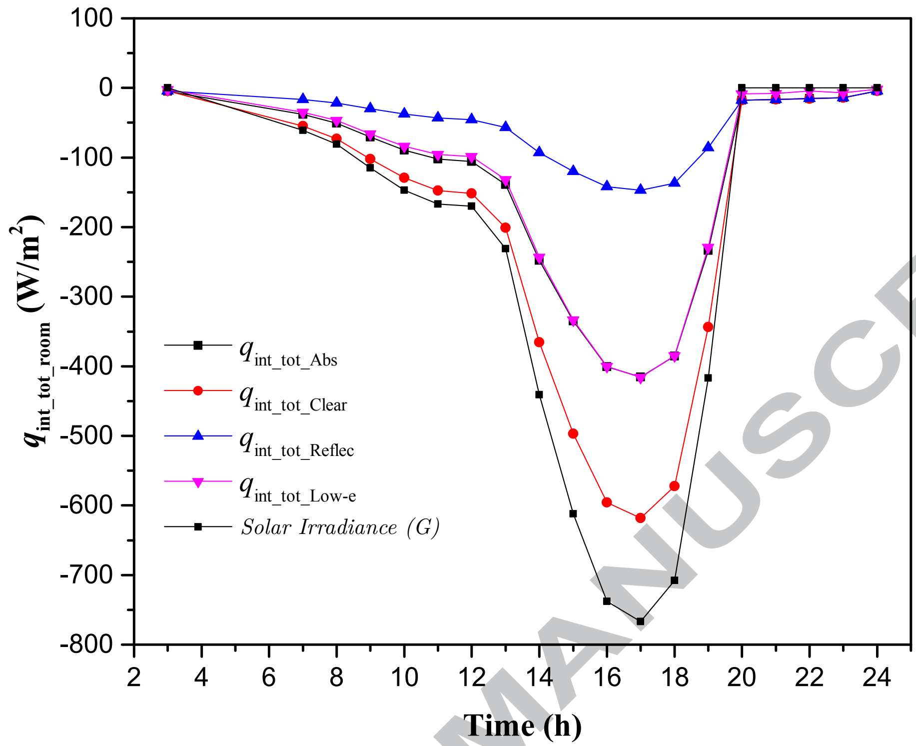

Figure 8: Average total heat flux inside the room for cases 1 to 4.

5.3. Energy savings and payback cost of DGW

5.3.1. Energy savings

The current price authorized by the Mexican Agency of Electricity for the Northeast Zone and two average domestic consumptions, domestic high consumption (rate 1) and low intermediate consumption (rate 2) were used. The rate 1 considers a consumption higer than 850 kWh per month and the rate 2 considers a consumption less than 300 kWh per month. Table 5 shows the total heat flux and energy cost ($USD) for warm condition and two domestic electricity rate. The energy savings analysis takes into account the q_{tot} as the total energy transferred to the indoors. *Case 1* is taken as a reference, as it the most commonly

Table 4: Total heat flux toward the indoors for all **DGW** cases analyzed.

Time (h)	$q^{C1}_{tot-int}$	$q^{C2}_{tot-int}$	$q^{C3}_{tot-int}$ [W/m^2]	$q^{C4}_{tot-int}$	$q^{C4}_{tot-int} - q^{C1}_{tot-int}$
00:00	-4.50	-4.44	-2.00	-4.49	**-0.01**
01:00	-4.50	-4.44	2.00	-4.49	**-0.01**
02:00	-5.07	-5.12	-2.31	-4.45	**-0.63**
03:00	-5.07	-5.12	-2.31	-4.45	**-0.63**
04:00	-5.07	-5.12	-2.31	-4.45	**-0.63**
05:00	-5.07	-5.12	-2.31	-4.45	**-0.63**
06:00	-5.07	-5.12	-2.31	-4.45	**-0.63**
07:00	-54.94	-38.04	-35.06	-16.39	**-38.55**
08:00	-72.97	-50.77	-46.76	-21.89	**-51.07**
09:00	-102.01	-70.63	-65.90	-29.77	**-72.24**
10:00	-129.36	-89.42	-84.01	-37.28	**-92.08**
11:00	-147.33	-102.14	-95.74	-42.92	**-104.41**
12:00	-151.77	-105.79	-98.56	-45.48	**-106.29**
13:00	-201.33	-138.77	-131.59	-57.07	**-143.28**
14:00	-365.35	-248.04	-243.55	-92.91	**-272.44**
15:00	-497.16	-334.99	-333.61	-120.28	**-376.88**
16:00	-595.60	-400.44	-400.34	-141.85	**-453.75**
17:00	-618.26	-415.54	-415.76	-146.85	**<u>-471.41</u>**
18:00	-572.48	-385.22	-384.72	-137.07	**-435.42**
19:00	-343.70	-233.61	-229.17	-85.91	**-257.78**
20:00	-17.89	-17.75	-8.67	-17.71	**-0.18**
21:00	-16.70	-16.59	-8.07	-16.56	**-0.14**
22:00	-15.41	-15.34	-4.40	-15.28	**-0.13**
23:00	-14.16	-14.07	-6.76	-14.03	**-0.13**
24:00	-4.50	-4.44	-2.00	-4.49	**-0.01**
Numerical Integration by trapezoid rule	**-3945.37**	**-2706.48**	**-2605.90** Wh/m^2	**-1065.99**	**<u>-2879.38</u>**

used in buildings and has the highest total heat flux.

The analysis performed to obtain the cost of the energy necessary to maintain the conditions of comfort in the room was based on the seasonal energy efficiency ratio (SEER), which relates the thermal energy necessary to maintain comfort with respect to the cost of that energy. Considering an inverter air conditioner of the minisplit type [48] with a SEER 15 (12,500 BTU/h, max) and the energy consumptions shown in Table 5. Converted to BTU/h, the power energy consumption is calculated for each case analyzed (Cases 1 to 4) during the warmest season of the year (May to October). In Table 5, the two rate analyzed are shown.

Rate 1 has a cost of $0.27 USD per kWh and Rate 2 $0.04 USD per kWh.

Table 5: Cost analysis for use DGW with two differente rates.

DGW Type	q_{tot_int} [kWh/m^2]	**Energy Cost** [$USD/year] **Rate 1**	**Energy Cost** [$USD/year] **Rate 2**
Case 1: Clear	-3.95	27.81	7.11
Case 2: Absorbent	-2.71	19.08	4.87
Case 3: Low-e	-2.61	18.37	4.69
Case 4: Reflective	-1.07	7.51	1.92

It should be noted that *Case 1* presents the greatest heat flow to the interior of the room and, therefore is the one that represents a greater expenditure of electrical energy to maintain the room at a comfortable temperature (24°C). Table 5 illustrates a savings of 31.4, 33.9, and 72.9% on the absorbent, Low-e, and reflective glasses, respectively, compared to a double clear glass. The similarity in energy savings between *Case 2* and *Case 3* is due to the global optical properties being similar, which can be observed in Table 1.

The DGW-Reflective has a low transmittance ($\tau^*_{Sol} = 0.07$), a moderate reflectance ($\rho^*_{Sol} = 0.29$) and a high absorptance ($\alpha^*_{Sol} = 0.64$). The energy absorbed by the glass in contact with the outside environment dissipates it to the outside through convection and radiation, wihch is why this type of glass considerably reduces the flow of energy to the interior of the room, coupled with the reduced energy transmitted to the interior and the air space between the glasses.

5.3.2. Payback cost of DGW

The payback cost of DGW, according to the energy that could be saved by using each, was calculated. Note that only warm climatic conditions were analyzed due to the major final consumption. The cost of each DGW analyzed and its payback period, considering an annual increase of 5% in electricity rates is presented in Table 6. The DGW-Clear does not appear in this table because is taken as a reference, i.e., energy savings with this DGW is considered to be zero.

Table 6: Payback period for each DGW analyzed.

DGW Type	**Cost** [$USD/m^2]	**Energy Savings** [$USD/half year] *Rate 1(DAC)*	**Energy Savings** [$USD/half year] *Rate 2 (1C)*	**Payback period** [years] *Rate 1, Rate 2*
Case 2: Absorbent	21	8.73	2.23	2.3, 7.9
Case 3: Low-e	100	9.44	2.41	10.8, 23
Case 4: Reflective	80	20.29	5.19	3.7, 13.8

Table 6 illustrates that the shortest period to recover the investment is with the DGW-Absorbent, for both rates. However, if 20 years of useful life is considered for each DGW, then from the year following the recovery of the investment, until the end of the useful life of each DGW, there is a savings of $261.1 USD, $208.0 USD, and $583.5 USD with the rate 1 (DAC) for the DGW *Case 2* (absorbent), *Case 3* (Low-e) and *Case 4* (reflective), respectively.

Moreover, in rate 2 there is more consevative savings: $52.4, $0, and $69.9 USD for *Cases* 2, 3, and 4, respectively. This indicates that *Case 2* has the lowest investment cost, the shortest recovery time, and an intermediate energy savings. On the other hand, *Case 3* does not present energy savings, since its investment recovery time is greater than its useful life of 20 years. Finally, *Case 4* provides considerable energy savings from investment recovery, making it the most advisable for use in a warm climate.

6. Conclusion

An evaluation of the thermal performance of four types of glass in a double pane window coupling to a room was carried out. Warm climatic conditions were considered for four cases: clear glass (*Case 1*), absorbent glass (*Case 2*), Low-e glass (*Case 3*) and reflective glass

(*Case 4*) and the following is concluded:

- *Case 4* achieved the highest energy savings at $\simeq 73\%$ less with respect to *Case 1*. *Case 2* and 3 have a similar behaviour, at $\simeq 34\%$ less than *Case 4*.
- The global balance costs indicate that *Case 4* is the best option for energy savings in a warm climate. It is possible to save up to \$20.29 USD per kWh per year in comparison to *Case 1*. On the other hand, *Cases 2* and 3 had an energy savings of \$8.73 and \$9.44 USD per kWh per year, respectively, in comparison to *Case 1*. The payback period for *Case 4* is 3.7 years and 2.3 and 10.8 years for *Cases* 2 and 3, respectively, taking into account electricity rate 1.
- The maximum energy savings for life of DWG is for *Case 4*, in which it is possible save \$583.5 USD.
- Despite DGW Low-e having a similar thermal behavior to DGW absorbent, the high cost of these in Mexico, make them infeasible to use, due to their long payback period.
- A double glass window with reflective glass, such as in *Case 4*, is highly recommended for Mexican locations with warm climates.

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Table 7: Nomenclature.

b	Width of the cavity between glasses, cm
C_p	specific heat, J kg$^-1 K^-1$
C_μ	coefficients of the turbulence model
DGW	double glass window
g	gravitational acceleration, 9.81 m s$^-2$
G	solar radiation, W m$^-2$
H	height of the room, m
H_2	height of the glass, m
k	turbulent kinetic energy
PCM	phase change material
q	heat flux, W m$^-2$
q_{ext}^{conv}	convection heat flux towards the exterior of the room, W m$^-2$
q_{int}^{conv}	convection heat flux towards the interior of the room, W m$^-2$
q_{ext}^{rad}	radiation heat flux towards the exterior of the room, W m$^-2$
q_{int}^{rad}	radiation heat flux towards the interior of the room W m$^-2$
SC	Shading Coefficient
SHGC	Coefficient of the Solar Heat Gain
T	temperature, °C
u	horizontal velocity, m s$^-1$
W	width of the room, m
x, y	dimensional coordinates, m
Greek symbols	
β	thermal expansion coefficient, K$^-1$
δ_{ij}	Kronecker deltas
ε	rate of dissipation of k, m^2 s$^-3$
λ	thermal conductivity, W m$^-1$ $^-1$
μ	dynamic viscosity, kg m $^-1$ s$^-1$
μ_t	turbulent viscosity, kg m $^-1$ s$^-1$
ρ	density, kg m$^-3$
σ_T	turbulent Prandtl number
subscripts	
conv	convection heat transfer
ext	external ambient
int	internal ambient
rad	radiation heat transfer
Room	room quantities
$1, 2$	1, 2

HIGHLIGHTS

1. Thermal evaluation of a Room coupled with different types of Double Glazing Window (DGW) is analyzed.
2. Four cases were simulated: *Case* 1: DGW (clear); *Case* 2: DGW (absorbent), *Case* 3: DGW (Low-e) and *Case* 4: DGW (reflective).
3. *Case* 4 presents the better energy saving of all cases analysed, ~73% lower than *Case* 1.
4. *Cases* 2 and 3 have a similar thermal behaviour, almost 34% less than *Case* 1.
5. The global balance costs indicate that *Case* 4 is the better option for energy saving in warm climate.
6. *Case* 4 allows us to save up to $20.29 USD per kWh in a year in comparison to *Case* 1.